# Primary Blast Injury After a Bomb Explosion in a Civilian Bus

ELIEZER KATZ, M.D.,* BOAZ OFEK, M.D.,† JACOB ADLER, M.D.,† HARRY B. ABRAMOWITZ, M.D., F.A.C.S.,† and MICHAEL M. KRAUSZ, M.D., F.A.C.S.*

**A 6-kg explosive charge detonated under a seat in the center of a crowded city bus in Jerusalem, killing three passengers immediately. Of the 55 survivors, all of whom were transferred to two major medical centers, 29 were hospitalized. Among those admitted, a high rate of primary blast injuries was found, including perforated ear drums (76%), blast lung (38%), and abdominal blast injuries (14%). Two of the latter patients suffered bowel perforations, which were diagnosed with considerable delay. Eight patients (31%) had sustained life-threatening trauma, consisting of a combination of primary, secondary, and tertiary blast injuries. The overall mortality rate was 10.3%. The large number of primary blast injuries, including the unexpected finding of bowel perforations, is explained by the high amplitude of the air pressure wave (3.8–5.2 atm) and its relatively long duration (2–3 msec) resulting from the detonation of the high-energy explosive charge in the small, enclosed space of the bus. Besides the usual wounds sustained by victims of an explosion that occurs in a confined space, the possibility of primary blast injury to the abdomen and to the lungs should be taken into account by the treating surgeon.**

*From the Departments of Surgery, Hadassah University Hospital,* and Shaare Zedek Medical Center,† Jerusalem, Israel*

TERRORIST ACTIVITY against civilian targets is increasing all over the world, bringing in its wake injuries that are usually associated with military exploits. The casualties arriving at the emergency room of a general hospital after a bomb explosion often suffer from injuries that do not fall within the daily routine of the attending staff. A characteristic example is primary blast injury, which is inflicted by the sudden increase of the environmental air pressure resulting from the detonation of a high-energy explosive charge. In addition, the victims of violent explosions nearly always sustain other types of damage, such as penetrating wounds from flying debris (secondary blast injuries), blunt trauma from displacement of the body and its forceful impact with rigid and stationary objects (tertiary blast injury) and, finally, burns received from the flush of the explosion or from open fire, and smoke and dust inhalation (miscellaneous blast injury). The severity of these injuries is directly related to two factors: the magnitude of the explosion and the site of its occurrence (*i.e.*, whether it occurred in open air or in an enclosed space).[1-3]

The following is a report of our experience with blast injuries that were sustained during the explosion of a bomb in a civilian bus in Jerusalem. The pathophysiology of this specific trauma sustained in a small, confined space is discussed, and special attention is paid to the comparatively high rate of primary blast injuries found among the patients.

### The Explosion and the Casualties

An explosive charge corresponding to approximately 6 kg of TNT detonated under a seat in the middle of a crowded city bus in Jerusalem. At the time that the bomb went off, all of the windows of the bus were closed, thus making the space of the bus a confined space measuring $11.25 \times 2.15 \times 2.25$ m, with a volume of 54.4 $m^3$ (Fig. 1). From the force of the explosion, the metal plaits connected to the metal struts were blown to a distance of about 23 m, and the rear door was thrown 64 m from the vehicle. Based on these data, the air pressure changes inside the bus after the detonation were computed in relation to time and distance.[4] Thus, the calculated highest pressures inside the bus ranged from 3.8 to 5.2 atm, lasting for 2–3 msec until the walls were displaced outward. The impulse (*i.e.*, the integral of the pressure-time curve) was also calculated.[4] A detonation in an enclosed space engenders two impulses—namely, the direct and the re-

Reprint requests and correspondence: Eliezer Katz, M.D., Department of Surgery B, Hadassah University Hospital, P.O. Box 12000, 91120, Jerusalem, Israel.

Submitted for publication: September 19, 1988.

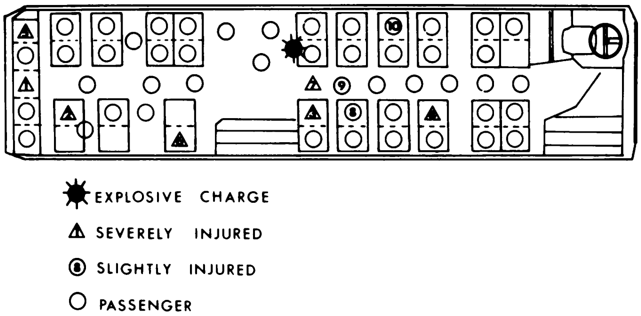


FIG. 1. Schematic illustration of the bus, showing placement of the explosive charge. The location of seven of the eight passengers with life-threatening multiple trauma (triangle) and of three of the slightly injured passengers (circle with numbers) at the time of the explosion could be established with certainty. The passengers whose exact location could not be discovered are depicted by the randomly dispersed empty circles. Note the distance of Passengers 1 and 5 (triangles) from the explosive charge, as compared with that of Patients 8, 9, and 10 (circles).

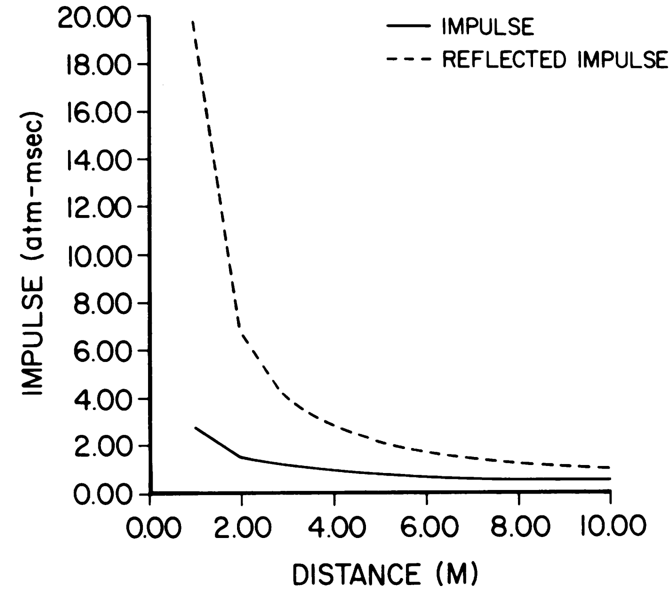


FIG. 2. The impulses inside the bus in relation to the distance from the focus of explosion. The direct impulse (—) represents the air pressure wave moving from the detonation site outward. The reflected impulse (—) represents the pressure wave bounced off a surface placed at right angles to its movement.

flected impulse. These impulses, as they occurred in the bus, are depicted in Figure 2 in relation to the distance from the explosion focus.

When the charge went off, there were 58 passengers in the bus. Three were killed outright. All of the others were transferred to two major medical centers, 42 to the one located about 200 m from the explosion site and 13 to a hospital about 2 km away. Of these 55 casualties arriving at the two emergency rooms, 29 (53%) were hospitalized, and 26 (47%) were discharged after examination and treatment.

The overall mortality (six of 58 patients) and that of the hospitalized patients (three of 29) was the same (10.3%). No details are available on the victims who died at the site of the explosion. Of the three patients who died in hospital, two had suffered severe head trauma and one succumbed to extensive burns (60% of body surface) (Table 1).

The injuries of the 29 patients admitted to medical centers are depicted in Figure 3. Unexpectedly, primary blast injury was a common trauma in this group (Fig. 4) and included 22 perforated ear drums (76%), eleven blast lung injuries (38%), and four abdominal blast injuries (14%). Two of the latter patients had perforation of the bowel, which involved the ileum in one patient and the colon in the other patient.

Eight of the 29 admitted patients (31%) had sustained life-threatening multiple trauma, which consisted of various combinations of the diverse forms of blast injury (Table 2). All eight patients suffered chest and lung damage, and all had perforated ear drums. Seven of these patients required emergency intubation, and two were in hemorrhagic shock. The two patients with perforated bowel belonged to this group of dangerously wounded individuals.

## Discussion

In its first phase, an explosion in the open air generates a blast pressure wave, which results from the compression of air by the explosive gases. The pressure wave advances outward from the site of the detonation at approximately the speed of sound, striking and moving everything in its path. Its force is directly related to the size of the explosive charge and reversely related to its distance at at a given time from the site of explosion.[1-3] In the second phase, the vacuum created at the explosion site produces an opposing, inward-moving pressure wave, which again strikes and forcibly displaces everything it encounters.[1-3] The destructive forces of each of these pressure waves account for the severe blunt and penetrating trauma that constitutes the secondary and tertiary blast injuries.

TABLE 1. *The Injuries Sustained by the Three Patients Who Succumbed After Arrival at the Hospital*

| Patient No. | Age (years) | Type of Injury | Day of Death |
|---|---|---|---|
| 1 | 13 | Severe open-head trauma | 1 |
| 2 | 16 | Left frontotemporal open fracture<br>Transverse sinus bleeding<br>Right eye enucleation<br>Left hemothorax<br>Hypovolemic shock | 3 |
| 3 | 60 | Blast lung injury<br>ARDS<br>60% burns | 13 |

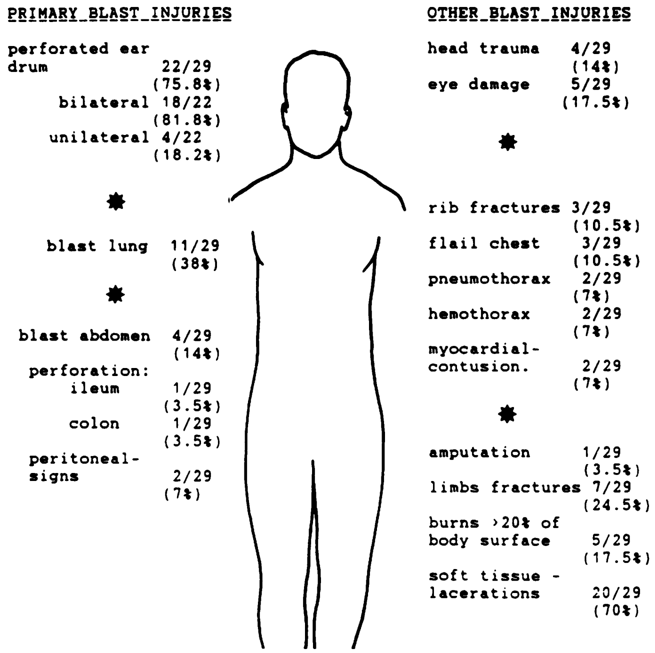


FIG. 3. The injuries of the 29 patients admitted to medical centers. The detonation of the high-energy explosive charge in the confined space of the bus resulted in a wide spectrum of primary and other blast injuries.

Primary blast injury, which is unique to the detonation of an explosive charge, has a much more complex pathophysiology. It characteristically involves organs that contain gas or gas and water, such as the eardrums, lungs, and bowel. The blast wave is reflected by the air-fluid interphase, with resultant tearing and disruptive forces that act on the surface of the fluid (the spalling effect).[2,5] The differences in tissue density and the compression and re-expansion of air-bubbles (implosion) were also suggested as factors in the pathophysiology of this singular injury.[2,5] The degree of severity of primary blast injury is

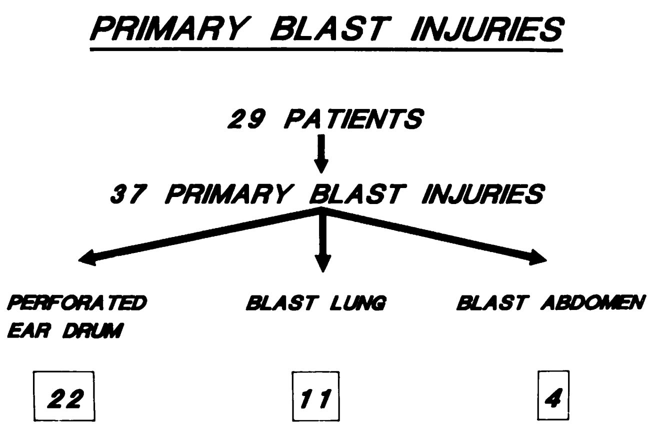


FIG. 4. Distribution of the 37 primary blast injuries sustained by the 29 hospitalized patients. The figures in the squares signify the number of patients suffering from the specific injury.

TABLE 2. *Details of the Injuries in the Eight Patients with Life-Threatening Multiple Trauma*

| Injury | Patients No. | Patients % |
|---|---|---|
| Hemorrhagic shock | 2 | 25 |
| Emergency intubation | 7 | 87.5 |
| Primary blast injury | | |
| Perforation of eardrums | 8 | 100 |
| Blast lung | 6 | 75 |
| Perforation of bowel | 2 | 25 |
| Other blast injuries | | |
| Head trauma | 2 | 25 |
| Chest and lung trauma | 2 | 25 |
| Burns | 2 | 25 |
| Comminuted fractures | 3 | 37.5 |

a function of the intensity of the pressure wave and its duration.[2,3,5]

An ever-recurring aftermath of an explosion is perforation of the eardrums, the least severe form of primary blast injury, although it may occasionally be accompanied by dislocation of the ossilles and damage to the inner ear.[1-3,6,7]

To the best of our knowledge, primary blast injury of the bowel has always been considered a consequence of underwater explosion only, which, according to the reported rates (0–1.2%), rarely occurs.[2,3,5,8-11] This belief that has previously been taken so for granted is dispelled by our findings with four of the 29 hospitalized casualties (14%) with primary abdominal blast injury, two of whom proved to have free bowel perforations. The injury to the bowel, most often involving the ileocecal region,[5,8] includes serosal tears, subserosal and intramural hemorrhages, as well as perforations. The latter either occur acutely or develop in areas of ischemic necrosis of contused bowel a few hours to several days after the forceful impact of the air wave that accompanies an explosion.[5,9,10,12]

In patients who have been exposed to high pressure air waves and who display no signs of external abdominal damage, the detection of an eventual perforated bowel is liable to be delayed. Such diagnostic oversight stems from the subacute nature of the perforation on the one hand, and from the presence of additional injuries that may mask the less obvious perforated bowel, on the other. Because the present event occurred on land, none of the treating physicians entertained the possibility of primary blast injury to the bowel. And, indeed, regarding the two patients ultimately discovered to have perforation of the bowel, the diagnoses of perforation of ileum in one patient and of colon in the other patient were delayed for 3 and 7 days, respectively. It is of interest that both of these patients suffered bilateral rupture of the ear drums and primary lung blast injury. The concomitant existence of these injures emphasizes the need for a high index of suspicion when treating patients who were exposed to a high-pressure air wave. We assume that the bowel perforations found in our patients are, to a large extent, due to the effect of the detonation in the small space formed by the tightly closed bus.

In primary blast injury to the the lungs, the trauma is usually manifested by alveolar wall damage with intra-alveolar and interstitial hemorrhages, and by edema. Rupture of the alveolar walls and tears in the visceral pleura lead to pneumo- and hemothorax.[1-3, 13-16] The insult to the alveoli and pleura may cause air to enter the circulation, with consequent air embolization to various organs.[2,17]

The number of primary blast injuries in the lungs reported in the literature is quite low (Table 3). In a study of 1532 persons injured by terrorist bombing, Hadden et al.[18] reported 250 patients admitted to medical centers, only two of whom (0.8%) had primary blast lung injury. In the studies conducted by Brismar and Bergenwald[19] and by Cooper et al.,[20] the respective figures for primary blast lung injury were nine of 107 (8.4%) and five of 194 (4.8%) for patients admitted to medical centers. In view of these small numbers, the latter authors concluded that primary blast lung injury is "uncommon in civilian terrorist bombing."[20] Our findings of the much higher figure of 38% for primary blast injury to the lung resulting from terrorist action must be attributed to the particular circumstances of the bus under discussion.

The diagnosis of primary blast injury of the lung is based primarily on symptoms and signs such as dyspnea, cyanosis, hypoxemia, and bloody tracheal secretion, whereas on chest x-ray, linear or patchy diffuse infiltrates (Fig. 5), pneumothorax and/or hemothorax can be found. Pulmonary insufficiency may be manifest shortly after exposure to the explosion, or may develop during the first or second day thereafter.[1,12,13,19]

In patients with overt pulmonary symptoms and findings and in whom there is no evidence of direct chest trauma, the diagnosis of primary blast lung injury is relatively simple. However, in those with severe blunt chest trauma, the differentiation between primary and tertiary blast injuries is extremely difficult. In such instances, the degree of pulmonary insufficiency, the severity of the blunt trauma (tertiary blast injury), combined with detailed analysis of the chest x-rays may help elucidate the presence of primary blast lung injury. It must also be pointed out that in casualties brought in with ruptured eardrums—which indicates exposure to high-pressure waves—the possibility of blast injury to the lung should not be overlooked. In the current series of patients, the diagnosis of primary blast lung injury was established according to the above criteria. It should be noted that we excluded those cases in which primary blast injury of the lung could not be proven with certainty because of severe chest contusion.

TABLE 3. *Reported Frequency of Primary Blast Lung Injury*

| Authors | Year | Total No. of Patients | Patients with Blast Lung Injury No. | Patients with Blast Lung Injury % |
|---|---|---|---|---|
| Hadden et al.[18] | 1978 | 250 | 2 | 0.8 |
| Brismar and Bergenwald[19] | 1980 | 207 | 9 | 8.4 |
| Cooper et al.[20] | 1983 | 104 | 5 | 4.8 |
| Present study | | 29 | 11 | 38.0 |

Hadden et al.[18] discovered histopathologic evidence of primary blast injury to the lungs in 45% of the victims who died at the site of an explosion, indicating the high probability of this damage in the more severely wounded patients. In fact, their findings are borne out by our findings of primary blast injury in six of the eight severely wounded patients (75%).

The exceptionally high proportion of primary lung and bowel blast injuries in our series must be ascribed to the action of the large explosive charge that detonated in the small and, what is of prime importance, *enclosed* space. Air pressure of 5 PSI (pounds/square inch) or more causes eardrum rupture, 16 PSI causes lung damage, and a mag-

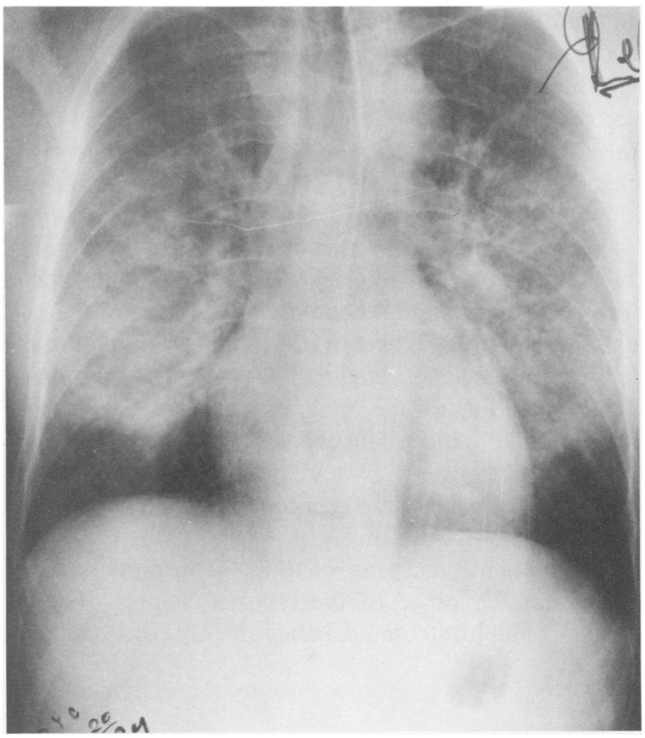

FIG. 5. Chest x-ray (PA) of one of the patients with primary blast lung injury, 6 hours after the explosion. Note the bilateral patchy infiltrates. This patient had no signs of external chest trauma.

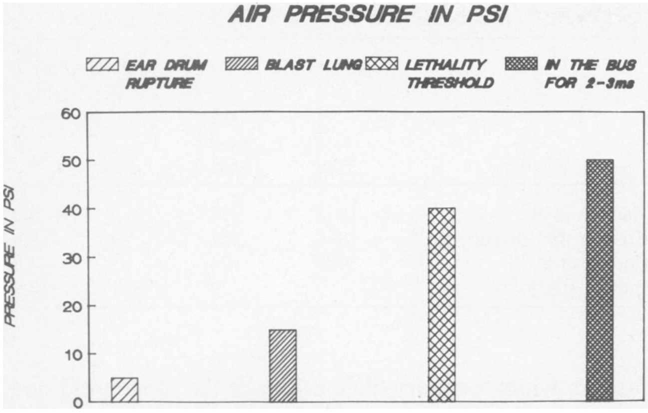


FIG. 6. The pressures inside the bus upon explosion of the charge in relation to pressures known to cause rupture of the eardrums, blast lung, and lethal outcome.

nitude of 30–42 PSI is defined as the lethality threshold pressure.[1,2] In the bus under discussion, the pressure reached a peak of 40–60 PSI for 2–3 msec (Fig. 6). Presumably, these extreme forces explain the considerable amount of primary blast injuries sustained in our patients, as well as the high rate of admittance (53%) and number of severely wounded patients (31%), as compared with the 15–20% reported in the literature.[1,18-20]

The relatively low frequency of primary blast injuries quoted in other studies is due to the fact that they were incurred in open air or large localities, where the zone of high pressure responsible for this specific trauma is limited and thus affects only those who are in close proximity to the core of the explosion.

In our study, analysis of the severity of the injuries as related to the distance of the patients from the core of the explosion revealed no correlation between these two variables. Patients 1 and 5 (Fig. 1) were gravely wounded, although they had been relatively far from the detonating charge, whereas Patients 8, 9, and 10, who had been much closer to the center of the explosion, suffered only slight injuries. These apparently conflicting sequelae of the exploding bomb must be attributed to the phenomenon of the pressure waves reflected and augmented by the sides of the bus, meanwhile striking passengers scattered throughout the vehicle. This effect is, of course, in contrast to blast injuries caused by an explosion in the open air or underwater, where the magnitude of the pressure wave drops linearly with distance.

The overall mortality rate of 10.3% in the present study falls within the range of the reported figures of 0.6–40%.[1,18-20] Fatal outcome depends mainly on secondary and tertiary blast injuries, and usually bears no direct relation to the primary blast injury.[1,20] Severe head and brain damage, the chief cause of death, accounted for 60% of 305 reported fatalities.[21]

Blast injury sustained in a small, enclosed space is one of the most serious and complicated forms of multiple trauma. Civilian hospitals must be prepared to counter this menace of modern times. In addition to the more common consequences of blast injury, the staff should also be familiar with the special aspects of this kind of trauma, so as to be able to make the correct evaluation and diagnosis, and initiate the proper treatment. The majority of blast victims who survive transfer to the hospital can be successfully treated.

## References

1. Stapczynski JS. Blast injuries. Ann Emerg Med 1982; 11:687–694.
2. Rawlins JSP. Physical and pathophysiological effects of blast. Injury 1978; 9:313–320.
3. Phillips YY. Primary blast injuries. Ann Emerg Med 1986; 15:1446–1450.
4. Proctor JF. Internal blast damage mechanisms computer program. Naval Ordinance Laboratory AD-759002.
5. Harmon JW, Haluszka M. Care of blast-injured casualties with gastrointestinal injuries. Military Med 1983; 148:586–588.
6. Pahor AL. Blast injuries to the ear: an historical and literary review. J Laryngol Otol 1979; 93:225–251.
7. Kerr AG. Trauma and the temporal bone: the effects of blast on the ear. J Laryngol Otol 1980; 94:107–110.
8. Adler J. Underwater blast injury. Med Bull US Army Europe 1981; 38:33–35.
9. Cameron GR, Short RHD, Walkeley CPG. Abdominal injuries due to underwater explosion. Br J Surg 1942; 31:51–66.
10. Gill WG, Hay CP. A clinical study of injuries of the abdomen due to underwater explosion. Br J Surg 1943; 31:67–73.
11. Huller T, Bazini J. Blast injuries of the chest and abdomen. Arch Surg 1970; 100:24–30.
12. Hamit HF. Primary blast injuries. Industr Med 1973; 3:14–21.
13. Hirsch M, Bazini J. Blast injury of the chest. Clin Radiol 1969; 20:362–370.
14. Weiler-Ravell D, Adatto R, Borman JB. Blast injury of the chest: a review of the problem and its treatment. Isr J Med Sci 1975; 11:268–274.
15. Coppel DL. Blast injuries of the lungs. Br J Surg 1976; 63:735–737.
16. Caseby NG, Potter MF. Blast injuries of the lungs: clinical presentation, management and course. Injury 1976; 8:1–12.
17. Freund U, Kopolovic J, Durst A. Compressed air emboli of the aortas and renal artery in blast injury. Injury 1980; 12:37–37.
18. Hadden MA, Rutherford WH, Merrett JD. The injuries of terrorist bombing: a study of 1532 consecutive patients. Br J Surg 1978; 65:525–531.
19. Brismar B, Bergenwald L. The terrorist bomb explosion in Bologna, Italy, 1980: an analysis of the effects and injuries sustained. J Trauma 1982; 22:216–220.
20. Cooper GJ, Maynar RL, Cross NL, et al. Casualties from terrorist bombings. J Trauma 1983; 23:955–967.
21. Hill JF. Blast injury with particular reference to recent terrorist bombing incidents. Ann R Coll Surg Engl 1979; 61:4–11.